Dual-Frequency 780-nm Ti:Sa Laser for High Spectral Purity Tunable CW THz Generation

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***Abstract*— A two-axis, two-polarization, dual-frequency Ti:Sa laser optimized for high spectral purity CW-THz generation is demonstrated. The laser output power is 50mW. Its mean emission wavelength is optimized around 780nm in order to suit the maximum efficiency of low temperature grown GaAs photomixers. Despite the extremely wide gain bandwidth of Ti:Sa, a proper intracavity filtering design, adapted to this particular laser architecture, enables tunable and single-frequency operation of each laser mode. The resulting beatnote is shown to be tunable between DC and 1.5 THz by steps of 82GHz. Its linewidth is narrower than 30 kHz without any active stabilization or cavity insolation.**

***Index Terms*—dual-frequency laser, solid-state lasers, terahertz, tunable.**

I. Introduction

Continuous-wave, tunable THz radiation can be obtained from the beating of two optical fields on a photoconductive antenna [1][2]. The design usually encountered for THz emission on such antennas relies on the beating of two independent lasers [1][3]. Alternative sources has been proposed, such as two longitudinal-mode lasers [4], or tunable dual-color laser [5][6]. Semiconductor lasers are compact and low cost, however they suffer from a relatively poor spectral quality, because of the short carrier recombination time and of the Henry factor [7]. On the contrary, solid state dual-frequency lasers offer a much better spectral purity [8][9]. In a dual-frequency laser, the two optical eigenmodes oscillate with crossed polarizations, and can thus be tuned independently. Furthermore, since the two laser modes oscillate in the same cavity, their frequency fluctuations are strongly correlated and cancel out almost perfectly on the frequency difference. The relevance of this solution was demonstrated in ref [8] at 1.03 µm in a Yb^{3+}:$KGd(WO_4)_2$ laser, and in refs [9][10] at 1.55 µm, using a Er:Yb-doped glass as an active medium. Unfortunately, the most mastered and widespread ps lifetime photoconductive material is LT-GaAs, that requires illumination at optical wavelengths around 800 nm [2]. Given its broad emission spectrum [11], Ti:Al_2O_3 is a natural candidate for tunable dual-frequency emission at 800 nm. The main difficulty of this approach is the obtainment of single-frequency emission and tunability on both polarization directions because of the extremely wide gain spectral width of Ti:Al_2O_3. Indeed, the most common technique to ensure single mode operation of a Ti:Al_2O_3 laser relies on designing a ring cavity, to get rid of spatial hole burning, in which a Lyot filter and multiple etalons are inserted. Such architecture does not apply for a dual frequency laser which is by essence closed by a linear cavity and which must sustain the oscillation of two crossed polarizations. In the following, we describe how we have designed the laser cavity and the pump geometry in order to obtain dual-frequency and dual-polarization operation. In this work, we report tunable dual-frequency emission from a compact Ti:Sa laser, and demonstrate the high spectral purity of the associated radiofrequency beat note.

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II. Laser Design

The dual-frequency laser cavity is represented in Fig. 1. It includes two Ti:Sa crystals as gain media, pumped by a 532 nm single-frequency laser (Coherent, Verdi-12). The cavity is a short plano-concave resonator closed by mirror M_2, whose radius of curvature is 5 cm. M_1 is a plane mirror coated for maximum reflection (R=99.9%) in the range 740–860 nm and for high transmission (T > 95%) at 532 nm. M_2 is a customized mirror with a maximum reflectivity of 95 % at 780 nm, and a reduced bandwidth of around 20 nm (see Fig. 2).

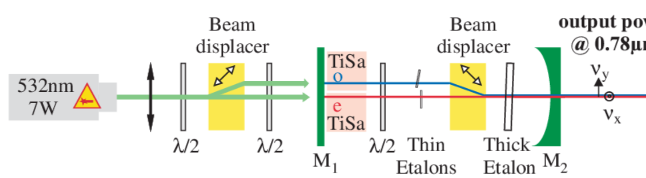

Fig. 1. Schematic diagram of the laser. λ/2: half wave plate. M_1: plane dichroic mirror, M_2: 95% output coupler, o: ordinary axis, e: extraordinary axis.

The laser operates near the end of the stability region, it thus gives a free spectral range close to 2.4 GHz with all intra-cavity components. The cavity is chosen as short as possible, that is, around 5 cm in order to facilitate single mode oscillation.

The spectral selectivity of the output coupler M_2 is displayed in Fig. 2, where the amplified spontaneous emission spectrum, obtained when the laser is pumped below threshold, is measured using either a standard mirror (740nm-860nm) or the narrowband M_2 mirror as output couplers. We can note that, when M_2 is used, the bandwidth of the oscillator is drastically reduced to about 10 THz, centered at 780 nm.

AR coated optics are used to focus the pump inside the $Ti{:}Al_2O_3$ crystal. The pump beam waist in the laser crystals was measured to be 40 µm, so that the Rayleigh range is about 7 mm, comparable with the crystal length of 5 mm.

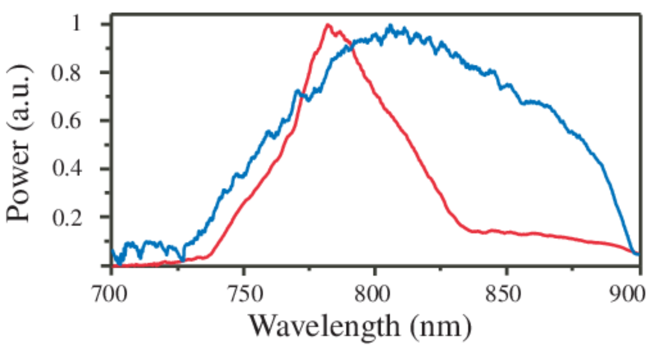

Fig. 2. Amplified spontaneous emission spectrum using a standard output coupler (blue) and the customized narrowband M_2 mirror (red).

Spatial separation inside a portion of the cavity is needed both for independent tuning of each eigenfrequency, and for obtaining a frequency difference larger than the cavity free spectral range [16]. In order to obtain two separated pump beams, a birefringent YVO_4 crystal cut at 45° of its optical axis (Roditi, 5x5x18.36 mm, AR @ 532 nm) is used as a beam displacer. At the crystal end, the two pump beams are spatially separated by 2 mm and orthogonally polarized. Given the fact that the absorption and emission cross-sections of Ti:Sa are anistropic [12], we have inserted two separated lasers crystals (Roditi, 4x4x5 mm, doping 0.25 % weight, figure of merit FOM > 150) as active media with their c-axes mutually orthogonals. A second birefringent crystal is thus necessary to recombine the oscillating modes inside the laser cavity. Because of its good transparency, we have chosen a calcite crystal (Moltech, 5x5x18.82 mm, AR @ 800 nm) to compensate the 2-mm beam separation at 780 nm. The crystal length is calculated to optimize the overlap of the ordinary and extraordinary modes with the two pump spots at 780 nm. In principle, the overlap is not perfect for other wavelengths because of dispersion. However, in practice this effect is negligible and does not lead to a degradation of the Gaussian spatial profile of the output beam. For example, a wavelength shift of 3 nm, necessary to obtain a 1.5 THz beat-note, entrains a lateral displacement of the cavity mode waist of less than 0.6 µm. The lasing threshold is obtained for a pump power of 2 W on each arm when all the elements are inserted in the cavity.

We now detail the role of the intracavity elements that are used for spectral selectivity, namely the half-wave plate (HWP) and the étalons.

At first, two thin étalons were inserted on the two separated arms of the laser cavity. These filters are fused silica plates of thickness 25 µm, optical index n=1.47 @ 780 nm, and coated in order to have an intensity reflection coefficient R=50 %. When the étalon is perpendicular to the ordinary propagation axis, the laser oscillation occurs near 782nm and tunability on a few nms is possible. The FSR of the thin étalons is of 8.3 nm or equivalently 4 THz. For other solid-state lasers such as two-axis $Yb^{3+}{:}KGd(WO_4)_2$ or Er:Glass lasers[8][9], the presence of a rather similar thin étalon is sufficient to ensure stable single-frequency operation. We found that it was not the case here. In some particular cases, single frequency may be obtained near threshold. Nevertheless, we observed, using a high resolution spectrometer (“Zoom Spectra”, Resolution Spectra System Inc) whose resolution is comparable to the free spectral range of the laser cavity, that in general the thin étalon does not provide strong enough selection on adjacent modes of the laser cavity, which are separated by only 2.4 GHz. Thus the “fine” spectral selectivity must be improved. Moreover, even if most of the times one observes a single peak in the optical spectrum for each polarization, under some experimental conditions lasing was observed on two consecutive longitudinal modes of the thin étalon, despite their separation of 8.3 nm. Thus, also the “coarse” spectral filtering provided by M_2 is not sufficient, given the enormous gain bandwidth of Ti:Sa. The situation that is typically encountered is illustrated in Fig. 3. The optical spectrum displays a single peak for each polarization (Fig. 3(a)), but each peak shows a fine structure due to the presence of some (typically 2-3) laser cavity longitudinal modes (Fig. 3(b)).

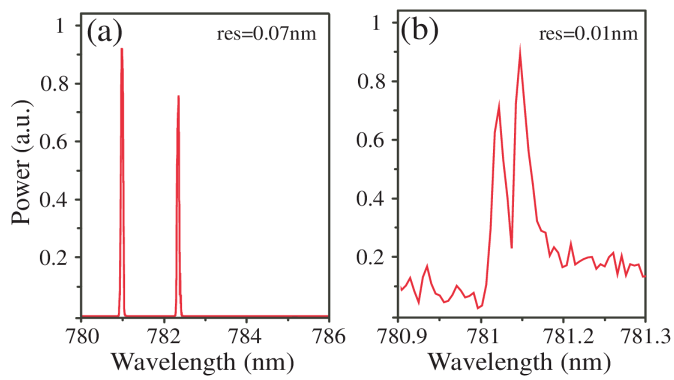

Fig. 3. (a) Optical spectrum of the two-axis laser. With respect to Fig.1, the intracavity HWP and thick étalon are absent. The two peaks correspond to ordinary and extraordinary polarization respectively. (b) Zoom on the first peak, showing that additional filtering is required to get single-frequency emission for each polarization.

The difficulty in filtering adjacent longitudinal cavity modes is due to the spatial hole burning that is present in a linear, standing-wave laser resonator [13]. This difficulty is usually circumvented by designing a ring laser cavity [14], but this cannot be done for dual frequency lasers. Compared to refs [8][9] where the active medium length is 2mm, our longer 5mm long Ti:Sa crystal contributes to enhance spatial hole burning effect.

In order to improve the spectral selectivity, we cannot consider increasing the reflection coefficient of the thin etalon further. Indeed, the reflection coefficient is already quite high, and increasing it further might lead to multiple cavity effects and would induce important losses when the étalon is tilted, thus limiting the oscillator tunability [15]. Thus, we have chosen to add a thick étalon (1 mm thick YAG plate, n= 1.82, uncoated) on the common path of the two modes. This étalon has a free spectral range (FSR) of 82 GHz. The presence of this filter was found to suppress efficiently adjacent laser cavity modes, thus solving the issue of fine spectral selectivity. Nevertheless, under some conditions two modes of the thin étalons could still be observed, requiring an increase of the coarse selectivity.

In principle, the coarse filtering could be improved by decreasing the thickness of the thin étalon, or by reducing further the bandwidth of the mirror M_2, but both options turned out to be technically unfeasible. So, we resorted to an additional spectral filtering technique which takes advantage of the presence of a polarization walk-off crystal inside the cavity. To this end, we inserted a HWP in the cavity. The HWP neutral axes are at 45° to the ordinary and extraordinary polarizations, so that the laser polarization remains linear, and its direction is rotated by 90°, if the wavelength is an exact multiple of the HWP optical thickness. On the contrary, for all other wavelengths the polarization becomes elliptical, and this results in intracavity losses when the beam passes through the intracavity calcite crystal. Thus the combination “HWP+birefringent crystal” forces the laser to oscillate preferentially on the HWP resonances. Note that the HWP plate must be placed where the modes are spatially separated, otherwise forked cavity eigenstates are obtained [16]. The losses induced by the HWP plate depend on the plate order, i.e., its thickness. We used an 11^{th} order plate centered at 780 nm. This introduces sufficient losses on the adjacent modes of the thin étalon to guarantee single frequency operation far from laser threshold.

The combined action of all the spectral filters resulted in stable and tunable single-frequency emission on each laser arm. The total output power is of 50 mW when pumped with 6.4 W. Tunability is obtained by tilting the thin étalons and is analyzed thanks to the high resolution spectrometer (Fig. 4). The frequency difference can be conveniently tuned from a few GHz up to 1.5 THz, corresponding to the frequency bandwidth of LT-GaAs photoconductive materials. Obviously, the frequency difference variations are not continuous because the laser modes “jump” by steps of 82 GHz corresponding to the free spectral range of the YAG plate.

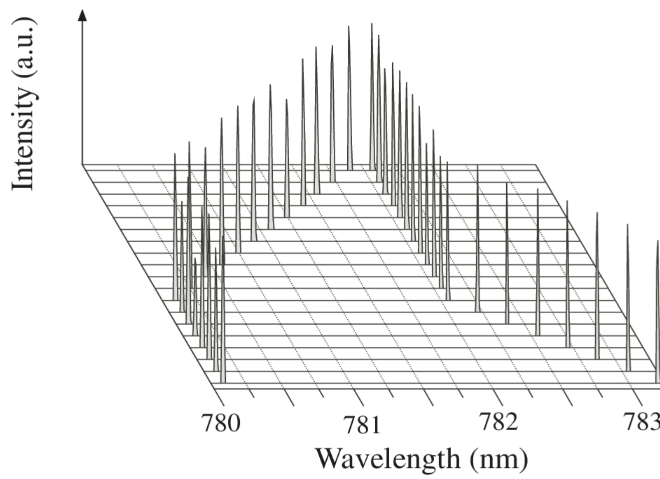

Fig. 4. Optical spectrum of the two-axis laser as one intracavity thin étalon is tilted while the second one is fixed. Note that each wavelength can be tuned independently. Res 0.01nm.

In order to detect and characterize the beating between the two laser modes, we have used a 10GHz GaAs photodiode directly connected to an electrical spectrum analyzer. To this end, we have tuned the laser so that the two lasing wavelengths could not be distinguished on the high resolution optical spectrum analyzer. Then, by placing the photodiode after a polarizer, we have recorded the electrical spectrum of the beat-note signal. We note that the beat-note signal amplitude can always be optimized by suitably orienting the polarizer, even if the intensities of the two polarizations are not exactly the same. In particular, this allows compensating for variations of the output power that occur after wavelength tuning.

As illustrated in (Fig. 5(a)) one observes a single peak, thus confirming that only one longitudinal mode for each polarization of the laser cavity (FSR = 2.4 GHz) is present. By zooming this peak, it is possible to measure the linewidth of the beat-note signal (Fig. 5(b)), which is found to be around 30 kHz with a resolution bandwidth (RBW) of 30 kHz and a measurement time of 0.3 s.

The drift of the beat-note frequency is measured to be of a few tens of MHz over a minute. We have checked that the laser exhibits the same performances in terms of linewidth and frequency drift whatever its mean wavelength. Despite the relatively high pumping power, the presence of two active crystals in the laser and different filtering levels, these performances are similar to that usually obtained with a less complex two axis dual frequency laser at 1.55 μm [10]. These results are very encouraging since the inherently narrow beatnote that is achieved makes it possible to envisage down conversion and phase-locking to a microwave local oscillator provided that a voltage controlled tunability is implemented to the laser [17].

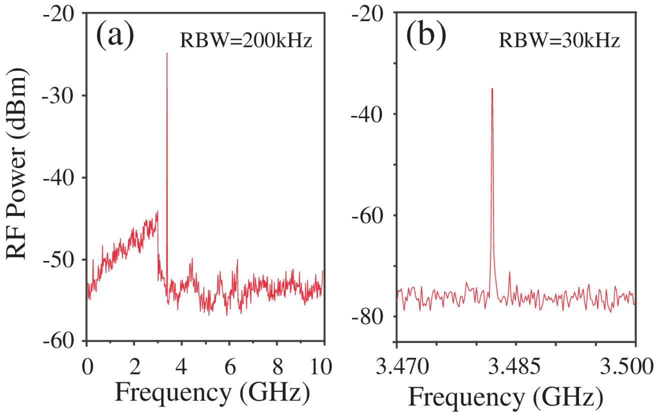

Fig. 5. Electrical spectrum of the beat-note in the microwave domain. The photocurrent signal is detected by a fast GaAs photodiode. (b) Zoom on the beat-note. RBW 30 kHz, measurement time 0.3 s.

III. Conclusion

We have built a compact THz-beatnote two-frequency Ti:Sa laser oscillating around 780 nm. By a proper cavity design and wavelength filtering, tunable single-frequency operation has been achieved on both polarizations independently, thus providing tunable beat notes spanning from the GHz up to the THz range by steps of 82 GHz. The optical output power is around 50 mW, which should allow us the generation of some µWs in the THz range with state-of-the-art photomixers [18]. The linewidth of the beat-note has been measured to be around 30 kHz without any acoustic or thermal insulation. The long term drift of this beatnote is a few tens of MHz over a minute without any stabilization. The next step is to implement to this laser a voltage controlled tunability in order to phase lock the beatnote to a local oscillator after down conversion. Given its operating mean-wavelength around 780 nm, this system provides a valuable alternative to produce high spectral purity CW THz radiation taking advantage of the LT-GaAs photomixing technology. Alternatively, it might be optimized for Coherent Population Trapping in Rubidium.

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